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Abstract. LFEW is a low frequency electromagnetic wave detector mounted on TC-2, which can measure the magnetic fluctuation of low frequency electromagnetic waves. The frequency range is 8 Hz to 10 kHz. LFEW comprises a boom-mounted, three-axis search coil magnetometer, a preamplifier and an electronics box that houses a Digital Spectrum Analyzer. LFEW was calibrated at Chambon-la-Forêt in France. The ground calibration results show that the performance of LFEW is similar to that of STAFF on TC-1. The first results of LFEW show that it works normally on board, and that the AC magnetic interference of the satellite platform is very small. In the plasmasphere, LFEW observed the ion cyclotron waves. During the geomagnetic storm on 8 November 2004, LFEW observed a wave burst associated with the oxygen ion cyclotron waves. This observation shows that during geomagnetic storms, the oxygen ions are very active in the inner magnetosphere. Outside the plasmasphere, LFEW observed the chorus on 3 November 2004. LFEW also observed the plasmaspheric hiss and mid-latitude hiss both in the Southern Hemisphere and Northern Hemisphere on 8 November 2004. The hiss in the Southern Hemisphere may be the reflected waves of the hiss in the Northern Hemisphere.

Keywords. Magnetospheric physics (Plasma waves and instabilities; Instruments and techniques) – Space plasma physics (Instruments and techniques)

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1 Introduction

Since the plasma in the magnetosphere is collisionless, the plasma wave, as a media of collective interaction, is very important in the magnetospheric plasma dynamic process. Waves can transform the energy from one region to another region in space. From a theoretical point of view, there are two kinds of waves in a collisionless plasma: electrostatic waves and electromagnetic waves. However, absolutely pure electrostatic waves are hardly observed in space. The electromagnetic waves have both oscillating electric and magnetic field components. Various electromagnetic waves in the magnetosphere are observed, whose frequencies can range from 10^{-3} Hz to 10^{9} Hz. Since the satellite itself generates magnetic fields, field sensors are always mounted on booms that extend outside the satellite.

LFEW is the first low frequency electromagnetic wave detector manufactured in China, which is designed to measure low frequency electromagnetic waves in the frequency range of 8 Hz–10 kHz. The Center for Space Science and Applied Research (CSSAR) of the Chinese Academy of Sciences is responsible for the design and manufacture of LFEW. The Center d'Environnement Terrestre et Planetaire (CETP) in France helped CSSAR to calibrate LFEW.

TC-2 is the polar satellite of DSP, with an apogee of 4 R_E and a perigee of 500 km. During the mission, TC-2 crosses many important space regions, such as the plasmasphere, radiation belt, auroral zone, cusp and polar cap. In these regions, there exists an abundance of wave activities, which provide the only effective coupling between particles. These

Fig. 1. The picture of the search coil and the electronic box of LFEW/TC-2.

waves have a close relation with solar wind conditions, geomagnetic storms and substorms.

The primary scientific objectives are the following:

• To study the generation mechanism and propagation characteristics of low frequency electromagnetic waves at the plasmapause, and the acceleration, diffusion and precipitation processes of the particles.

• To study the instabilities and generation processes of low frequency electromagnetic waves (e.g. ion cyclotron wave) in the auroral and cusp regions, and their accelerating effects on the upflowing ions (H^+, O^+ and He^+).

• To study the generation mechanism of low frequency electromagnetic waves (including magnetic pulsations and Alfvén waves) in the plasma sheet and the plasma sheet boundary layer during magnetospheric substorms and magnetic storms and their relationship with magnetospheric substorms, the heating, acceleration and diffusion processes of ionospheric upflowing ions and plasma sheet thermal ions that interact with these waves.

• To study the plasma instabilities at the dayside magnetopause boundary layer, the generation mechanism, frequency spectrum and propagation characteristics of low frequency electromagnetic waves and magnetic pulsations, and their effects on the transfer of solar wind energy into the magnetosphere.

2 Instrument description and commissioning results

The LFEW instrument comprises a boom-mounted three-axis search coil magnetometer, a preamplifier and an electronics box that houses a digital Spectrum Analyzer.

The instrument characteristics and measured parameters are as follows:

a) Mass: 3.6 kg
b) Power: 5 W
c) Measurement range: 8 Hz – 10 kHz
d) Scientific telemetry rate: 3 kbit/s
e) Size: Sensor $\phi 25\times 240\times 300\,\text{mm}^3$,
Electronic unit $150\times 180\times 200\,\text{mm}^3$.

Figure 1 shows the search coil and the electronic box of LFEW. The search coil consists of three mutually orthogonal sensors that are mounted on the end of a rigid boom that is 4.0 m away from the spacecraft center. Two sensors (B_y and B_z of LFEW) lie in the spin plane and the third (B_x) is parallel to the spin axis. The angles between B_y (B_z) and the boom is 45° with an accuracy of ±2°. The frequency response of the sensor is flattened in the frequency range 8–10 000 Hz by a secondary wind used to introduce flux feedback.

There are three preamplifiers located in the electronic unit inside the satellite. The dynamic range of the preamplifiers is 100 dB. The output signals of the preamplifiers are sent to the spectrum analyzer, which then calculates the power spectra density of the three components. The phase differences between the three components are also downlinked. The frequency range of 8 Hz–10 kHz is divided into three subbands:

(1) Low frequency band: 10–100 Hz
(2) Middle frequency band: 100–1000 Hz
(3) High frequency band: 1000–10 000 Hz.

There are 96 spectrum lines that are distributed over the three frequency bands (32 spectrum lines for each frequency band, some lines overlapped). The three frequency bands each have their own sampling rates:

(1) Low frequency band: 400 Hz
(2) Middle frequency band: 4 kHz
(3) High frequency band: 40 kHz.

For each of the three bands, there are three separate automatic gain controlled (AGC) amplifiers (for B_x, B_y, B_z respectively) and the gain of these AGC amplifiers has the role of a multiplying factor in the determination of the absolute measurement.

The digital processing of the output signals is in three distinct steps:

(1) De-spin of the spin-plane sensor outputs;
(2) Determination of the complex Fourier coefficients;
(3) Determination of the phase difference between the three components.

The de-spinning operation is necessary since the instrument measurement time interval is not short compared with the satellite spin period (4 s). Then the treatment of data on the ground will be able to transform the data from the satellite coordinate in to the GSE coordinates.

Since LFEW is the first Chinese low frequency electromagnetic wave detector, we made the design as simple as possible. Therefore, LFEW has only one operation mode and no in-flight calibration.

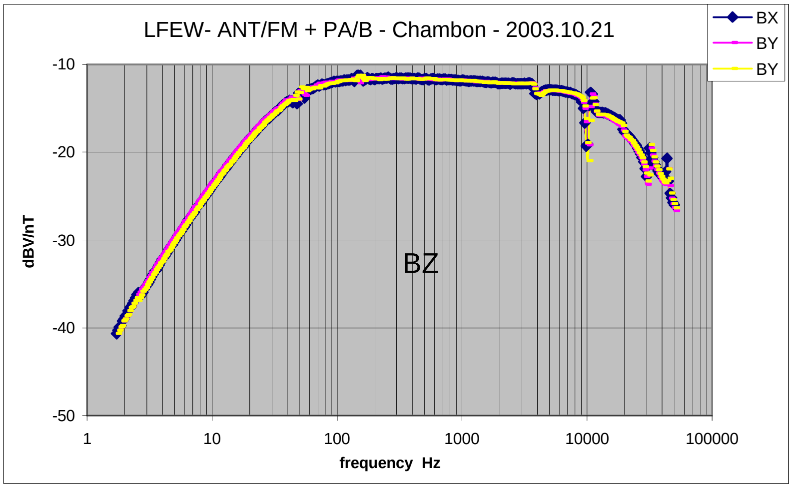

Fig. 2. The transfer functions of three axis search coils of LFEW/TC-2.

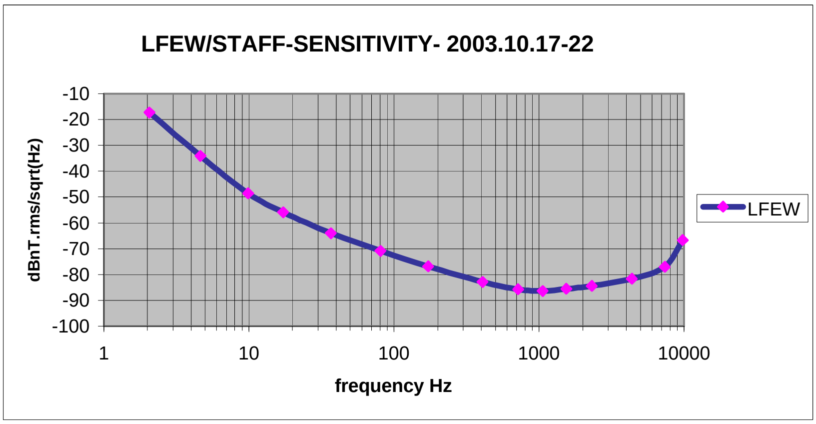

Fig. 3. The sensitivity measured in Chambon de Forêt of LFEW/TC-2.

From ground measurements, the sensitivity of the three mutually orthogonal sensors is 3.0×10^{-3} nT Hz$^{-1/2}$ at 10 Hz, 2.5×10^{-4} nT Hz$^{-1/2}$ at 100 Hz, 5.6×10^{-5} nT Hz$^{-1/2}$ at 1 kHz and 5.0×10^{-4} nT Hz$^{-1/2}$ at 10 kHz The similarities of the search coils for the three axes are good. The dynamic range of the associated preamplifiers is about 100 dB.

In October 2003, LFEW was calibrated at Chambon-la-Forêt, the same site used to calibrate the STAFF instrument of Cluster. Figures 2 and 3 show the transfer function and sensitivity of the search coils.

It can be seen that the performances of the three axes are almost the same. Generally, there will be less noise in the space than on the ground. Thus, the in-flight sensitivity is better than on the ground.

3 First results of LFEW of TC-2

We analyzed the data of LFEW and found many interesting wave activities. Some preliminary results are discussed below. More detailed studies of the physical process need to be done in the near future.

3.1 Ion cyclotron waves

Almost every time when TC-2 crossed the cusp in the Southern Hemisphere, waves with frequencies below the proton cyclotron frequency Ω_p were observed by LFEW.

Figure 4 shows the ion cyclotron waves observed by LFEW on 16 September 2004, which lasted from 21:17 to 21:39 UT. The blue line in Fig. 4 indicates the local proton cyclotron frequency on the satellite path. The satellite position at 21:31 is: $\boldsymbol{R}$=(0.38, 0.14, 1.04)R_E in SM coordinates, MLT=13.37, MLAT=–68.6° and IL=72.1°. The waves existed both in the plasmasphere and in the cusp. At the entry of the cusp, the waves are relatively weak. Deep in the cusp,

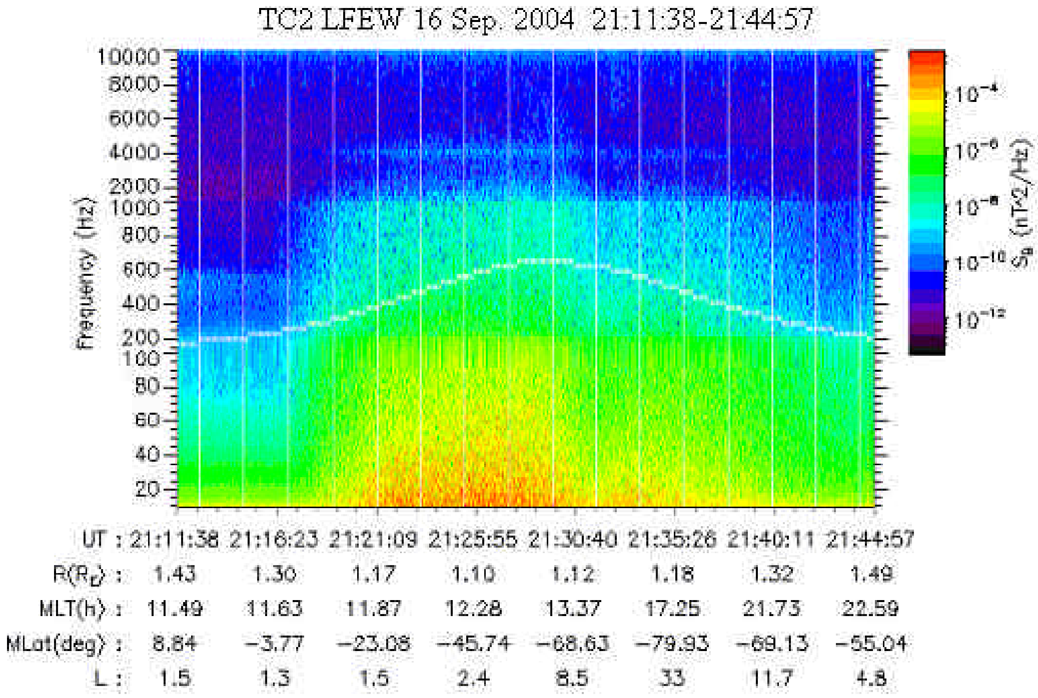

Fig. 4. Ion cyclotron waves observed by LFEW on 16 September 2004.

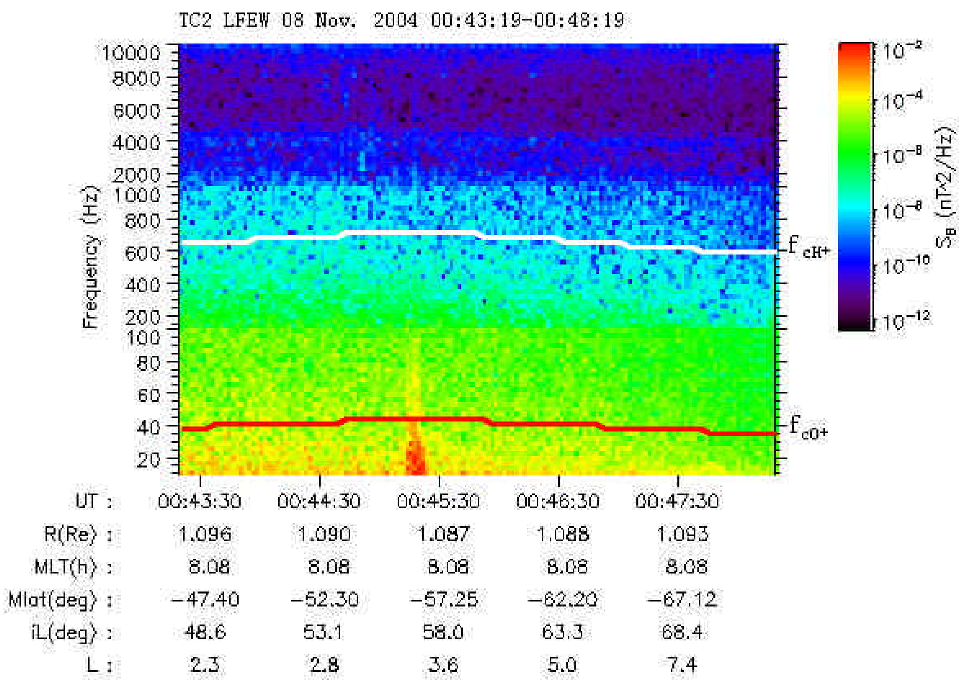

Fig. 5. The time-frequency spectrum observed by LFEW at 00:43:15–00:48:15 UT on 8 November 2004.

the waves become stronger than at the entry. The profile of the wave frequency spectrum seems to have a close relation with the proton cyclotron frequency.

Electromagnetic ion cyclotron waves were detected by many satellites in the plasmasphere (Kintner and Gurnett, 1977; Sonwalker, 1995). Their frequencies generally lie near the ion cyclotron frequencies. Generally, these ion cyclotron waves are excited by precipitating ring current ions

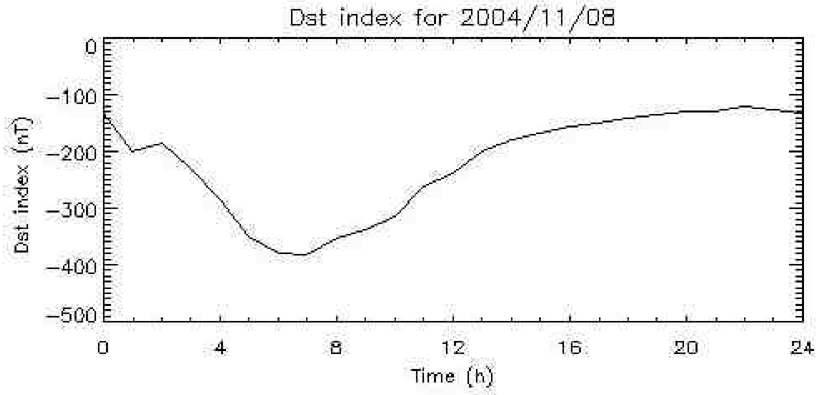

Fig. 6. D_{st} index on 8 November 2004.

(Sonwalker, 1995). Thus, the ion cyclotron waves between 21:17 and 21:30 UT may be generated by ring current ions.

Pfaff et al. (1998) have identified similar ULF-VLF (< few Hz) waves in the cusp using measurements from the Polar electric and magnetic field experiments, and have tentatively identified them as Alfv'en waves. D'Angelo et al. (1974) reported observations from OGO-5 in which ULF magnetic fluctuations were detected at the polar cusp boundaries and were probably due to the Kevin-Helmholtz instability. Gurnett and Frank (1978) reported the presence of a band of ULF-ELF magnetic noise extending from a few Hertz to several hundred Hertz at almost every cusp pass, using Hawkeye I data. They stated that this noise could be used as a reliable indicator of the polar cusp region.

Since the part of the waves in the cusp (from 21:32 to 21:36) is just below the proton cyclotron frequency, it is likely that they are the proton cyclotron waves. However, a more certain conclusion can only be drawn when we know the wave polarization.

3.2 Wave bursts during geomagnetic storms

During geomagnetic storms (particularly strong geomagnetic storms), LFEW often observed low frequency wave bursts whose duration was only around 10 s. The data analysis shows that the stronger the geomagnetic storm, the larger the wave burst amplitude. For example, from 00:45:13 to 00:45:24 on 8 November, LFEW observed a wave burst when the satellite was at the position MLT=8.08, MLAT=–56. and L=3.4 (see Fig. 5). The proton cyclotron frequency and oxygen cyclotron frequency are indicated by white a line and a red line.

On 8 November 2004, there is a strong geomagnetic storm. The main phase of geomagnetic storm begins at 21:30:00 on 7 November. Figure 6 shows the D_{st} index on 8 November 2004. Shawhan (1979) mentioned that OGO-5 often observed wave bursts in the plasmasphere and cusp during geomagnetic storms. The waves associated with cyclotron frequencies of heavier He^{+} and O^{+}were detected by many satellites (Mauk et al., 1981; Roux et al., 1982; Gurnett and Inan, 1988). For example, an event of ion cyclotron waves that was associated with oxygen ion cyclotron frequency was detected inside the plasmasphere by the DE 1 satellite (Gurnett and Inan, 1988). Therefore, it is likely that the wave burst at 00:45:13 is related to the ring current oxygen ion of the storm time.

3.3 Whistler-mode chorus observations

Whistler-mode chorus is an electromagnetic wave emission occurring in the Earth's magnetosphere. The generation of these wave packets is not yet well understood. It is most often accepted that chorus is generated by a nonlinear process based on the electron cyclotron resonance of whistler-mode waves with energetic electrons (Nunn et al., 1997; Trakhtengerts, 1999; Kennel and Petschek, 1966), taking place close to the geomagnetic equatorial plane (Burton and Holzer, 1974; LeDocq et al., 1998; Parrot et al., 2003; Santolík et al., 2004, 2005). The chorus frequency is closely related to the equatorial electron gyrofrequency.

LFEW often observed whistler mode chorus outside the plasmasphere, which lasted from several hundred Hz to several kHz. For example, from 08:37.30 to 08:42:30 on 3 November 2004, LFEW observed chorus outside the plasmasphere (see Fig. 7). This wave activity approximately has two frequency bands: ∼200 Hz–600 Hz and 800 Hz–1 kHz. The two bands are separated, since there is almost no wave activity between them. Like the chorus in Fig. 2 of Meredith et al. (2004), the waves of lower frequency band lasted longer than the waves of the higher frequency band.

3.4 Plasmaspheric hiss and mid-latitude hiss

Plasmaspheric hiss is a broad-band, structureless, extremely low frequency (ELF) electromagnetic emission, which occurs in the frequency range from a few hundred hertz to several kHz. This natural whistler mode emission is characteristically confined to higher-density regions associated with the Earth's plasmasphere (Dunckel and Helliwell, 1969; Russell et al., 1969; Thorne et al., 1973) or detached plasma regions

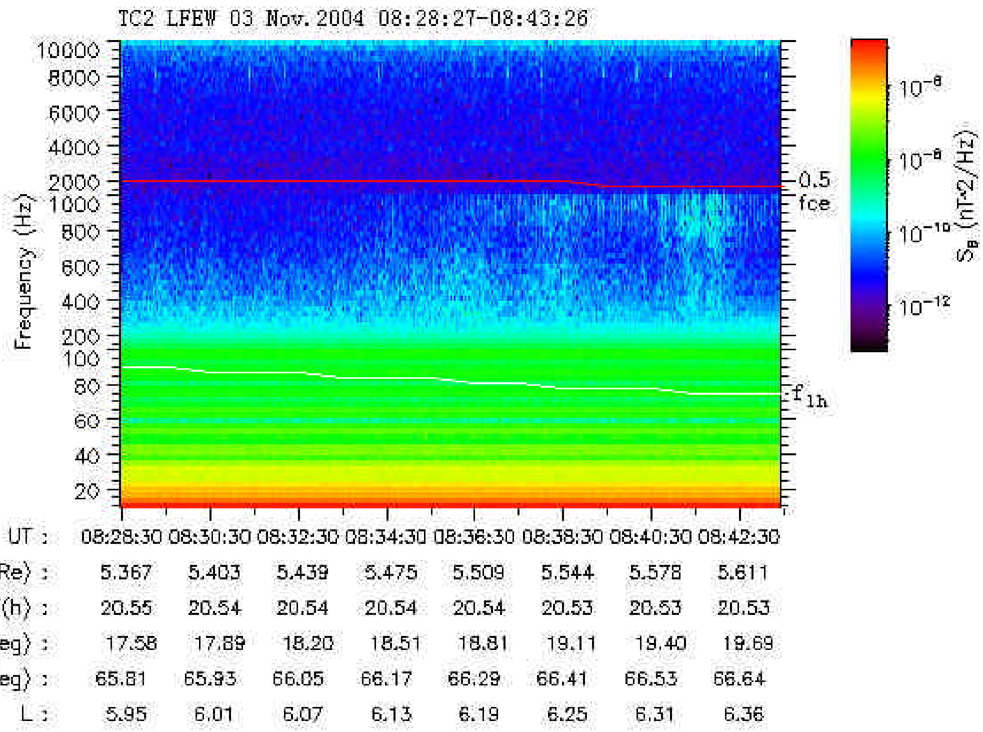

Fig. 7. The time frequency spectrum observed by LFEW at 08:28:30–08:43:30 UT on 8 November 2004.

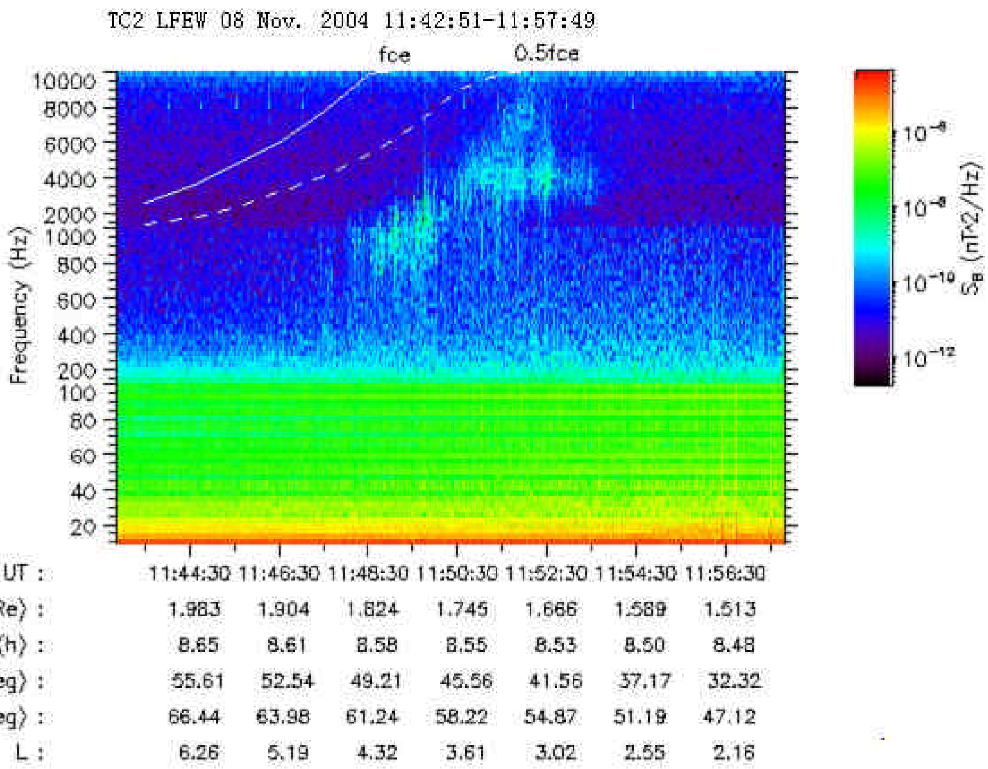

Fig. 8. Plasmaspheric hiss and mid-latitude hiss in the Northern Hemisphere observed by LFEW on 8 November 2004.

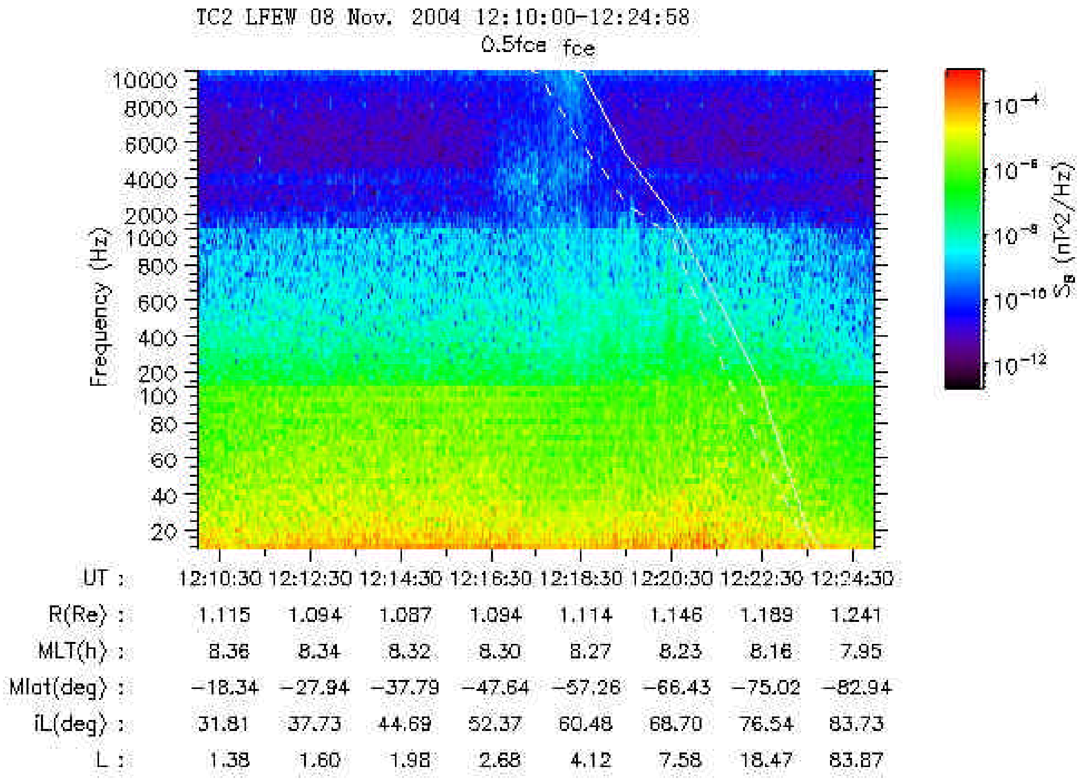

Fig. 9. Plasmaspheric hiss and mid-latitude hiss in the Southern Hemisphere observed by LFEW on 8 November 2004.

(Cornilleau-Wehrlin et al., 1978; Parrot and Lefeuvre, 1986). Plasmaspheric hiss can persist during relatively quiet conditions, but the emission intensifies during magnetic storms or substorms (Smith et al., 1974; Thorne et al., 1974, 1977). Wave intensification has been associated with the injection of plasma sheet electrons into the inner magnetosphere during substorms (Thorne and Barfield, 1976; Solomon et al., 1988; Cornilleau-Wehrlin et al., 1993).

In addition, the mid-latitude hiss between ∼2 to 10 kHz is often observed from the equator to subauroral latitudes. The maximum of their occurrence corresponded to the middle latitudes (55–65°) which are connected with the plasmapause projection (Hayakawa et al., 1975a, b, 1977, 1986, 1988; Dronov et al., 1985; Kleimenova, 1985).

The term "Plasmaspheric hiss" refers to hiss-type ELF emissions observed mostly inside the plasmasphere. The main energy of these emissions is concentrated in the frequency range 100 Hz–1 kHz, although their upper frequency limit could extend to a few kilohertz (Hayakawa and Sazhin, 1992), It seems possible that the high frequency part of the plasmaspheric hiss spectrum could sometimes result from the influence of mid-latitude hiss (Hayakawa and Sazhin, 1992).

When TC-2 crossed the plasmasphere, LFEW often observed waves with frequencies from ∼300 Hz to several kHz, which is between the local lower hybrid frequency and the equatorial electron cyclotron frequency. These waves are observed most often during magnetic quiet times and substorms.

Figure 8 gives an example of such waves on 8 November 2004. The wave activity lasted from 11:47:28 to 11:50:18 and 11:50:29 to 11:53:40 UT. The solid line and the dashed line in Fig. 8 indicated the equatorial gyrofrequency f_{ce} and half equatorial gyrofrequency 0.5 f_{ce}. The frequencies of the waves at 11:47:28 to 11:50:18 range from ∼300 Hz to 2.5 kHz. The frequencies of the waves at 11:50:29 to 11:53:40 range from ∼2 kHz to 8 kHz. Both instances of hiss occurred in the day sector.

Plasmaspheric hiss is stronger in the daytime sector compared to the midnight-to-dawn sector, and generally peaks at high (>40°) latitudes; The mid-latitude hiss between ∼2–10 kHz is often observed from the equator to subauroral latitudes, at all local times (Sonwalker, 1995). Thus, it is very likely that the lower frequency waves are plasmaspheric hiss and the higher frequency waves are mid-latitude hiss.

Mid-latitude hiss emissions are most likely to be generated in the equatorial magnetosphere where the energy of electrons is transferred to wave energy via the electron cyclotron instability. Some quantitative characteristics of these emissions are explained in terms of a quasilinear model of this instability. Plasmaspheric hiss is closely related to the same electron cyclotron instability, although the contribution of other mechanisms cannot be excluded (Hayakawa and Sazhin, 1992; Masson et al., 2004). Thus, sometimes it is very difficult to distinguish between plasmaspheric hiss and mid-latitude hiss. As mentioned in Sect. 3.2, a large geomagnetic storm comprising several substorms occurred on 8 November 2004. Therefore, the plasmaspheric hiss and mid-latitude hiss on 8 November were likely generated by substorm injected electrons.

Figure 9 shows another example of plasmaspheric hiss and mid-latitude hiss on 8 November 2004, which is similar to the hiss in Fig. 8. The interesting point of Fig. 9 is that the plasmaspheric hiss and mid-latitude hiss about Fig. 9 are almost exactly on the magnetic conjugate points of the hiss in Fig. 8.

Hayakawa and Sazhin (1992) pointed out that both mid-latitude and plasmaspheric hiss are generated in the equatorial magnetosphere and increase their wave normal angle when propagating away from the magnetic equator, unless there are cross-field gradients in electron density (which can occur, for example, in the vicinity of the plasmapause). When the wave frequency becomes equal to the local lower hybrid frequency, the waves are reflected back to the magnetic equator and thus become trapped within it. Therefore, it can be inferred that the hiss at 12:16:50–12:18:50 represents reflected waves of the hiss at 11:47:28–11:53:40.

4 Conclusions

This paper presents briefly the scientific objectives and characteristics of LEFW, and some of the preliminary results of LFEW. More in-depth work is needed to understand the physical process behind these waves.

The first results of LFEW show that it works normally on board, and that the AC magnetic interference of the satellite platform is very small. LFEW has observed various magnetospheric waves. For example, in the plasmasphere, LFEW observed the ion cyclotron waves. During the geomagnetic storm on 8 November 2004, LFEW observed a wave burst associated with the oxygen ion cyclotron waves. This observation shows that during geomagnetic storms, the oxygen ions are very active in the inner magnetosphere. Outside the plasmasphere, LFEW observed the chorus on 3 November 2004. Like the chorus in Fig. 2 of Meredith et al. (2004), the chorus of the lower frequency band lasted longer than the chorus of the higher frequency band. LFEW also observed the plasmaspheric hiss and mid-latitude hiss both in the Southern Hemisphere and Northern Hemisphere on 8 November 2004. The hiss in the Southern Hemisphere may be the reflected waves of the hiss in the Northern Hemisphere.

LFEW is the first Chinese low frequency electromagnetic wave detector. The design principle was to make LFEW as simple as possible so that LFEW coul work reliably. So we removed some functions from STAFF of TC-1. In a future mission, we hope to update the design of LFEW based on the experience obtained in the DSP mission. For example, we hope to add in-flight calibration, a burst mode and waveform output.

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